RESONANT COHERENT EXCITATION AS A HIGH PRECISION SPECTROSCOPY OF HIGHLY CHARGED IONS

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Channeled ions passing through a crystal along its axis or plane feel a periodic crystal field as a flux of virtual photons. When an excitation energy of the ions corresponds to the photon energy, resonant coherent excitation (RCE) takes place [1,2]. A typical resonance width, $\Delta E/E_{\mathrm{trans}}$, so far observed in the low energy region was ~10^{-2}, where E_{trans} is the transition energy, and ΔE is the resonance width. Recently, we succeeded in observing the RCE with relativistic ions, and found the resonance width, $\Delta E/E_{\mathrm{trans}}$, to be ~$10^{-4}$ [3]. This observation strongly indicates that the RCE provides a new and a unique technique of high precision spectroscopy of highly charged ions in X-ray region.

The RCE condition for planar channeling in a Si crystal is given by

$$E_{\mathrm{trans}} = \frac{ghv}{a}\left(\frac{k\cos\boldsymbol{q}}{A} + \frac{l\sin\boldsymbol{q}}{B}\right) \qquad (1)$$

where h is the Plank's constant, v is the ion velocity, $g = 1\big/\sqrt{1-(v/c)^2}$, c is the light velocity, a is the lattice constant of Si crystal, k and l are integers, $\boldsymbol{q}$ is the tilt angle from the [110] axis, and (A,B) = $(1/\sqrt{2}, 1/\sqrt{2})$, $(1/\sqrt{2}, 1)$ and $(1/\sqrt{2}, \sqrt{3/2})$ for (004), $(2\bar{2}0)$ and $(1\bar{1}1)$ planar channelings, respectively. The first order RCE condition (k = 1), which has a large transition amplitude, is realized only for ions with relativistic energies. Using 390 MeV/u Ar^{17+} ions supplied from Heavy Ion Medical Accelerator in Chiba (HIMAC) channeled in a Si crystal along the $(2\bar{2}0)$ plane, we observed the (k,l) = (1,1) RCE from 1s to n = 2 states (E_{trans} = 3.3 keV). A probability of ionization from an excited state is much larger than that from the ground state. Therefore, the RCE can be observed through measurements of the charge state distribution as a function of $\boldsymbol{q}$ in Eq.(1). For relativistic ions, a probability of non-resonant charge exchange is fairly small that the charge state distribution of transmitted ions is not smeared. Moreover, we can adopt a totally depleted silicon detector (SSD) with 31 μm-thickness as a target crystal, because the energy loss of the ions in the target is negligibly small compared with the incident energy. From the energy deposition to the SSD, we obtained the impact parameter dependence of RCE.

Fig.1 shows a fraction of Ar^{18+} ionized subsequent to RCE for ions passing through in the channel center called "best channeled ions", which correspond to the range of energy deposition from 2.5 to 2.8 MeV. The upper scale is the transition energy corresponding to $\boldsymbol{q}$ through the relation in Eq.(1). A two-peak (j = 1/2 and 3/2) structure originating from the spin-orbit interaction is clearly observed. The width (FWHM) of j = 3/2 peak is 1.1 eV. The beam angular divergence ($\Delta\boldsymbol{q}$ ~0.1 mrad) and the energy width of the incident beam ($\Delta E_0/E_0$ ~2×10^{-4}) affect the peak width, which amount to 0.44 and 0.78 eV, respectively. Because the

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RCE mostly occurs near the entrance surface of the crystal, the influence of the energy loss of the ion to the transition energy, which is estimated to ~0.08 eV, can be neglected. Therefore, the original resonance width is estimated to be $\sqrt{(1.1)^2 - (0.44)^2 - (0.78)^2}$ = 0.64 eV, *i.e.*, the relative resonance width, $\Delta E/E_{\mathrm{trans}}$, is ~2 $\times 10^{-4}$. The number of the atomic strings which contributes to the resonance, N, is evaluated from $\Delta E/E_{\mathrm{trans}} \sim 1/N$. In order to achieve such a sharp resonance, N should be ~5 $\times 10^3$, which corresponds to ~μm. Such a high coherence is realized by the large ion velocity, which is the most important advantage of using relativistic ions. By fitting a gaussian curve to the j = 3/2 peak as the dotted line in Fig.1, the peak position can be determined with a precision of ~0.05 eV, *i.e.*, ~10 ppm. The precision tells that the 1s-Lamb shift (1.14 eV for Ar^{17+}) is able to be determined with a precision in a few percent, which is already of the same order of the latest measurement [4]. At present, a precision of the determination of the absolute beam energy is insufficient. However, if the precise determination of the beam energy is achieved, the RCE measurement with relativistic heavy ions can be a useful tool for an atomic spectroscopy with a high precision.

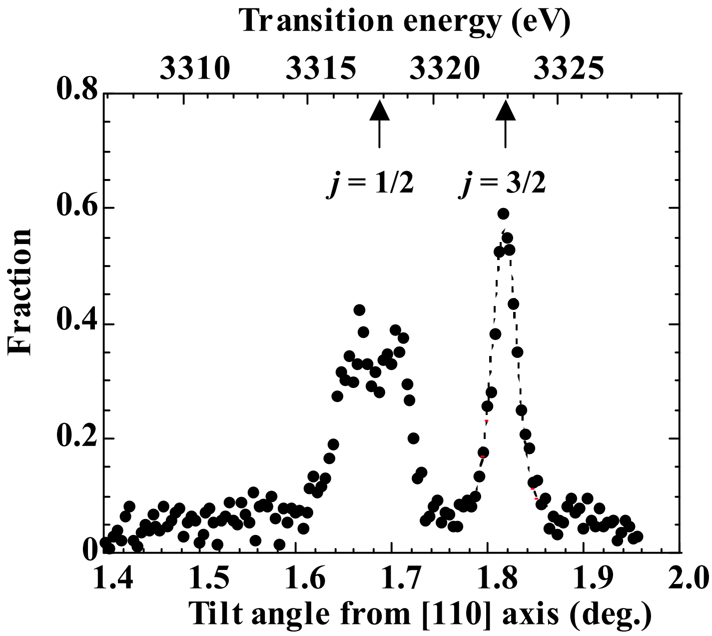

Fig.1 Fraction of Ar^{18+} ionized subsequent to RCE for best channeled ions as a function of the tilt angle from [110] axis. Dotted line is the fitting curve. Arrows indicate transition energies from 1s to n = 2 states (j = 1/2 and 3/2) in vacuum.

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